Optimization of high average power FEL beam for EUV lithography application

November 4, 2014 Dublin

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HiLASE Centre, Institute of Physics, Prague

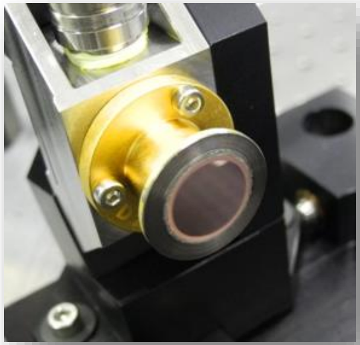
Development of Thin Disk-Based High Power Picosecond Laser Beamlines

Beamline-A

0.75 J, <3 ps, 1.73 kHz

1300 W

Sub-contract



Pulse compressor → 100 mJ, 1-2 ps, 1 kHz

100 W

Booster

Cryogenic Slab amplifier

Pulse compressor

1 J, 1-2 ps, 120 Hz

120 W

Beamline-B

Oscillator

Pulse stretcher

HERA

Pre

Regenerative Amplifier

Main

Ring amplifier

Pulse compressor

0.5 J, 1-2 ps, 1 kHz

500 W

Beamline-C

Oscillator

Pulse stretcher

Main

Regenerative Amplifier

Pulse compressor

5 mJ, 1-2ps, 100 kHz

500 W

Fyzikální ústav
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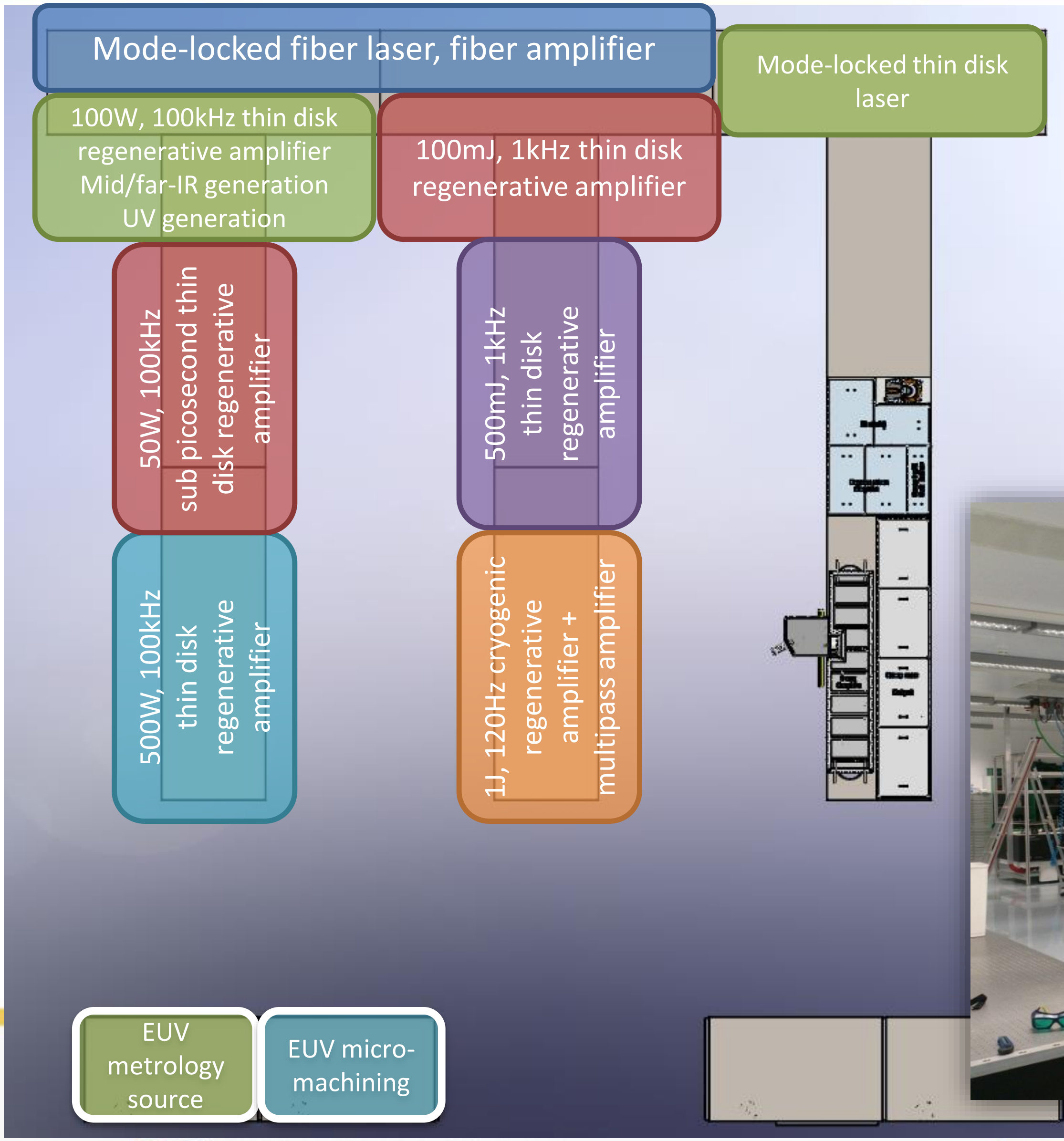
Layout of RP-1 Laboratory



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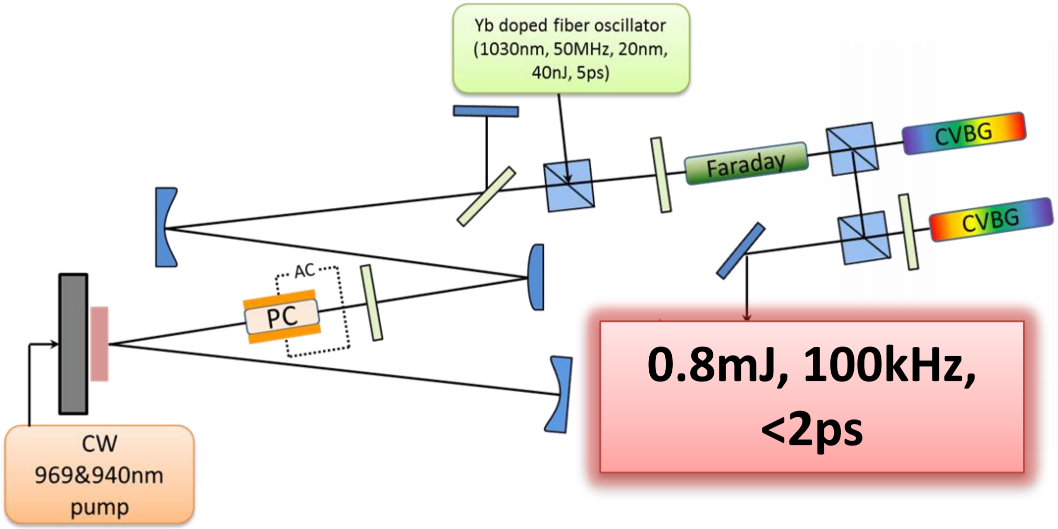
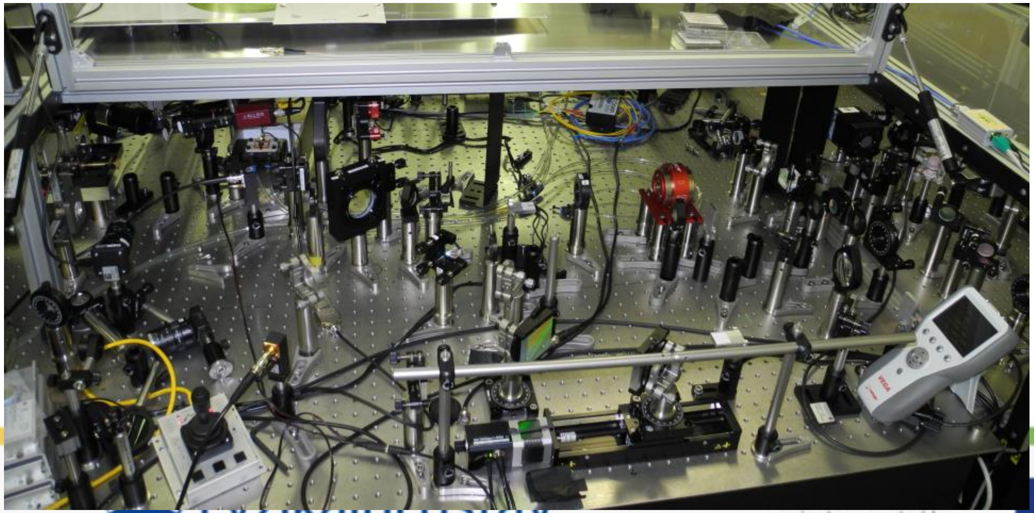
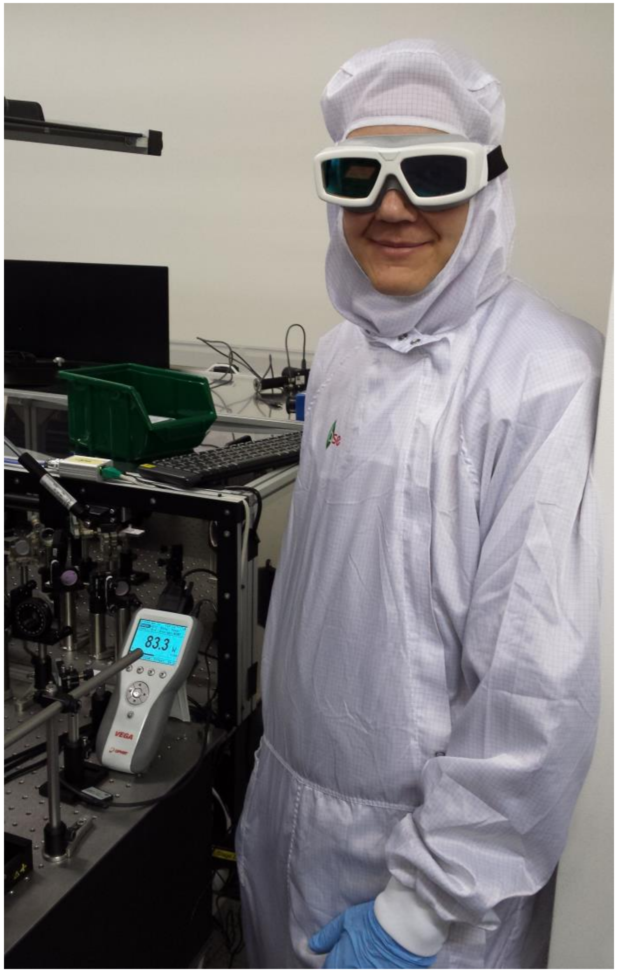
Beamline C - 85W (January 2014)



0.8mJ, 100kHz,
<2ps





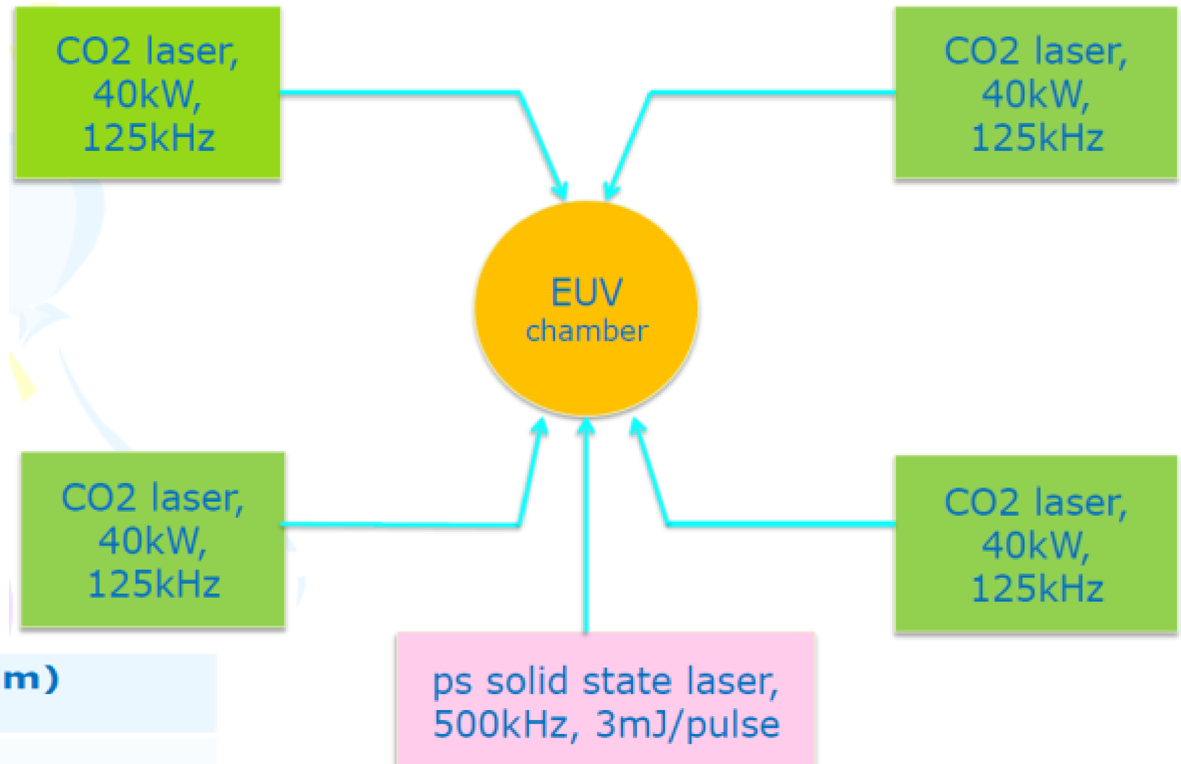
Outline

1. Scaling of LPP EUV technology to >kW
2. Potential of FEL technology to >kW, required optimization
3. Seeding of EUV FEL for kW, 13.5nm generation : UV, 100fs, >MHz, OPCPA laser

Scaling to shorter wavelength, multi kW operation

Scaling to 6.xnm,

kW source



Extendibility Evaluation of Industrial EUV Source Technologies for kW Average Power and 6.x nm Wavelength Generation Akira Endo
J. Modern Physics, 2014.5.285-295
Scientific Research

EUV IF power	**1kW (6.xnm)**
CO2 laser power	160kW
Conversion efficiency	1.5%/0/6%b.w. *
Collection efficiency	40%
Mirror reflectivity	70% **

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Scaling of SASE-FEL power

- MHz >100W
- 10MHz >1kW

FRA04 Optimization of high average power FEL for EUV lithography application

Akira Endo, Kazuyuki Sakaue,
Masakazu Washio : Waseda University
Hakaru Mizoguchi : Gigaphoton Inc.

FEL concept for EUV lithography

SLAC–PUB–15900

January 2014

FEL oscillator for EUV lithography*

G. Stupakov
SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
M. S. Zolotorev
Center for Beam Physics, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

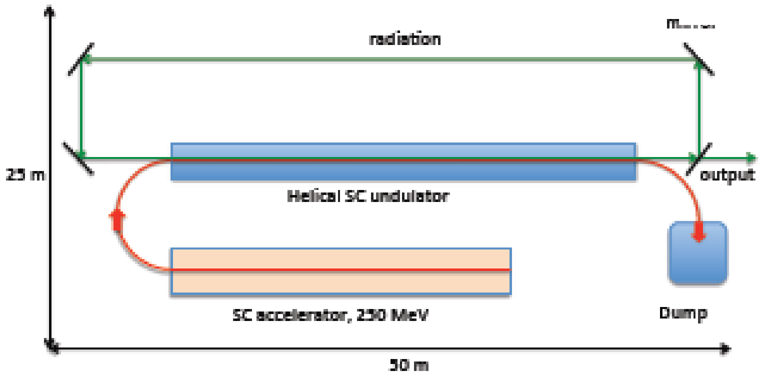


TABLE II. Parameters of the undulator

Period	5 mm
Free beam aperture	3 mm
Undulator parameter	0.4
Beta function	1.3 m
Undulator length	30 m

TABLE I. Beam parameters

Beam energy	240 MeV
Bunch charge	0.1 nC
Bunch length (flat profile)	1 ps
Peak current	100 A
Normalized slice emittance	0.3 mm mrad
Relative energy spread	10^{-4}
Length of accelerator	30 m
Repetition rate	5 MHz

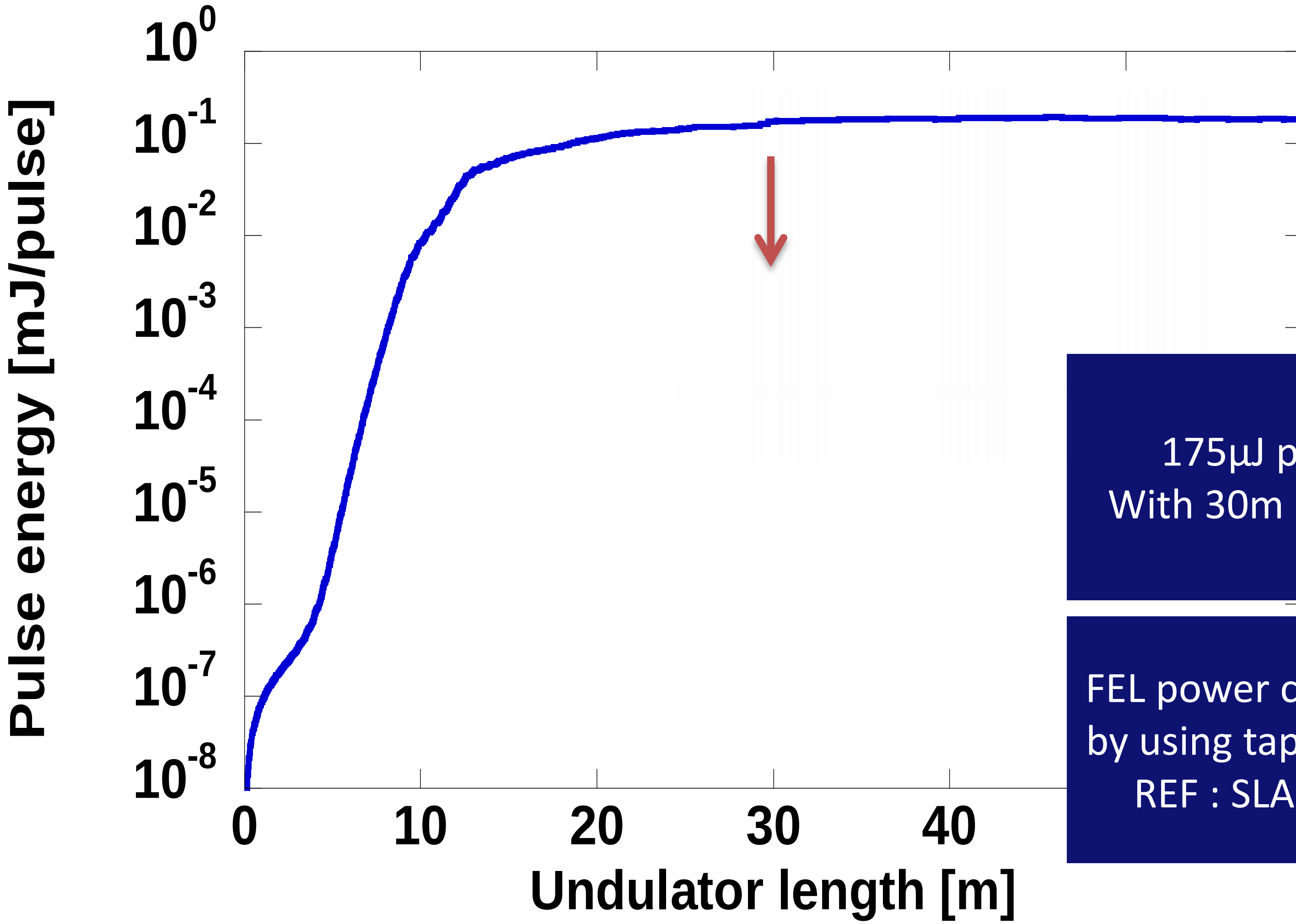
GENESIS Calculation Parameters

Based on near term realistic engineering

Parameter	Value
Charge	300pC
Emittance	1 mmmrad
Energy Spread	1 E-4
Bunch length	200fs
Energy	331.13MeV
Undulation Period	9mm
K Value	1

Calculation by K.Sakaue (Waseda University)

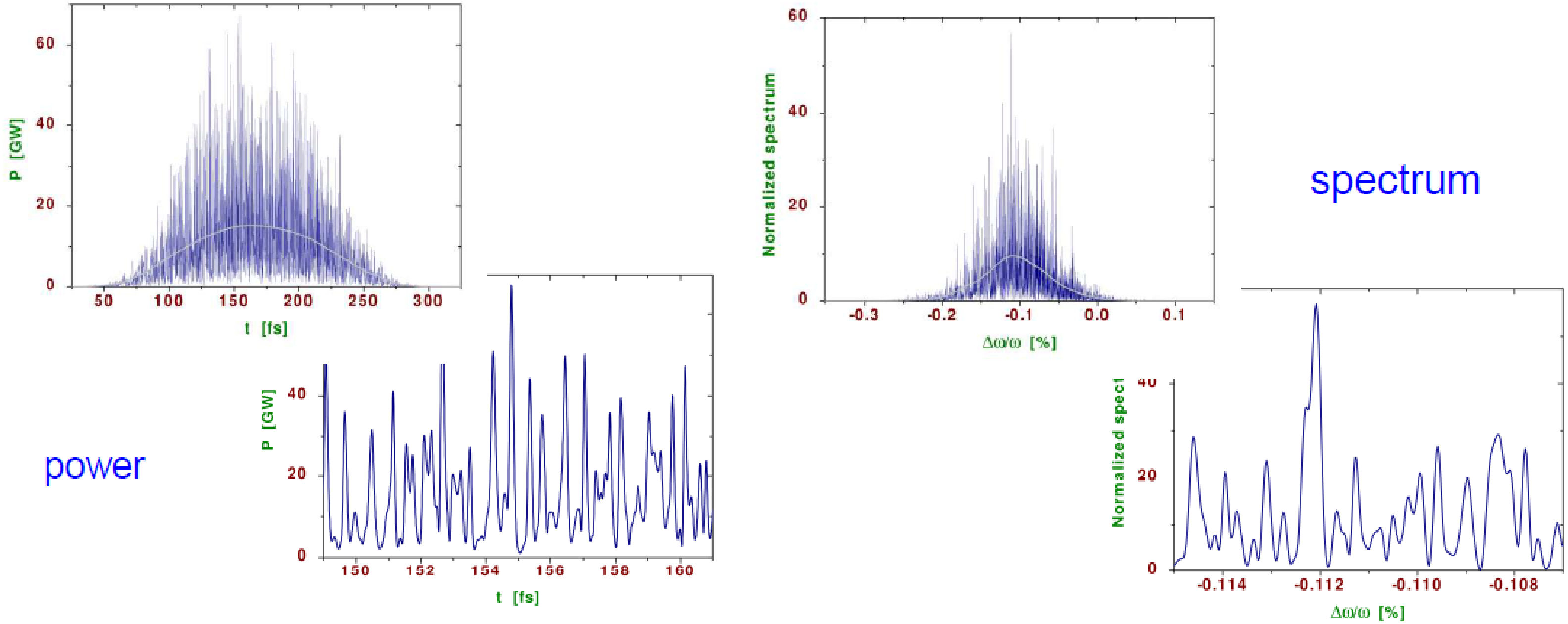
GENESIS Calculation



175μJ pulse energy
With 30m long undulator

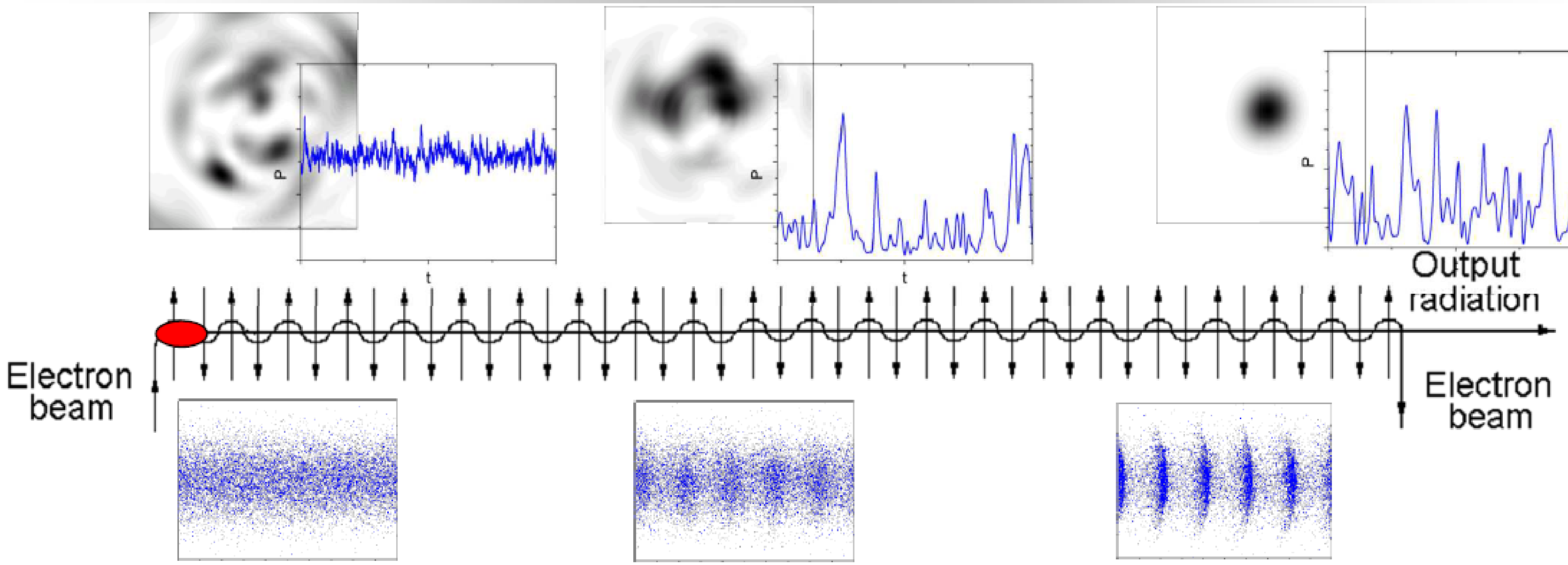
FEL power can be increased by using tapering undulator
REF : SLAC-PUB-15900

Qualitative look at the radiation properties



- Radiation generated by SASE FEL consists of wavepackets (spikes). Typical duration of the spike is about coherence time τ_c.
- Spectrum also exhibits spiky structure. Spectrum width is inversely proportional to the coherence time, $\Delta\omega \sim 1/\tau_c$, and typical width of a spike in a spectrum is inversely proportional to the pulse duration T.
- Amplification process selects narrow band of the radiation, coherence time is increased, and spectrum is shrinked.

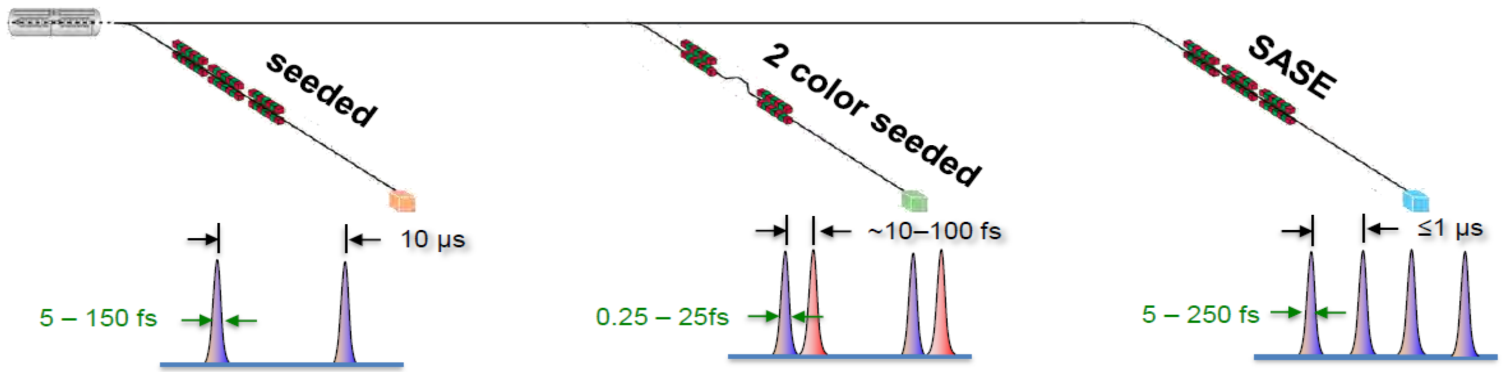
Qualitative look at the radiation properties



- Beam density modulations at frequencies close to the resonance frequency initiate the amplification process.
- Fluctuations of current density in the electron beam are uncorrelated not only in time but in space, too. Thus, a large number of transverse radiation modes are excited.
- Longitudinal coherence is formed due to slippage effects (electromagnetic wave advances electron beam by one wavelength while electron beam passes one undulator period). Thus, typical figure of merit is relative slippage of the radiation with respect to the electron beam on a scale of field gain length ➔ coherence time $\tau_c \sim \lambda L_g/(c\,\lambda_w)$.
- Transverse coherence is formed due to diffraction effects. Typical figure of merit is ratio of the transverse size of the electron beam σ^2 to the diffraction expansion of the radiation λL_g on a scale of the field gain length ➔ diffraction parameter B.

LCLS-II project for high repetition rate FEL

Three initial FEL beamlines to span the science case



- Up to 100 kHz
- High resolution
- ~Time-bandwidth limited
- $10^{11} – 10^{12}$ photons/pulse
- $10^{-3} – 5x10^{-5}$ $\Delta\omega/\omega$

- Up to 100 kHz
- Ultra-fast
- 250 as pulses
- Two color
- 10^{8} ph/pulse

- Highest rep rate, MHz and greater
- High flux
- 10^{11} - 10^{12} photon/pulse
- 100 W

NGLS offers significant advances over current capabilities:
- More photons per unit bandwidth
- More photons per second
- Shorter pulses
  - With controlled trade-off between time and energy resolution

ALS Users' Meeting 2011

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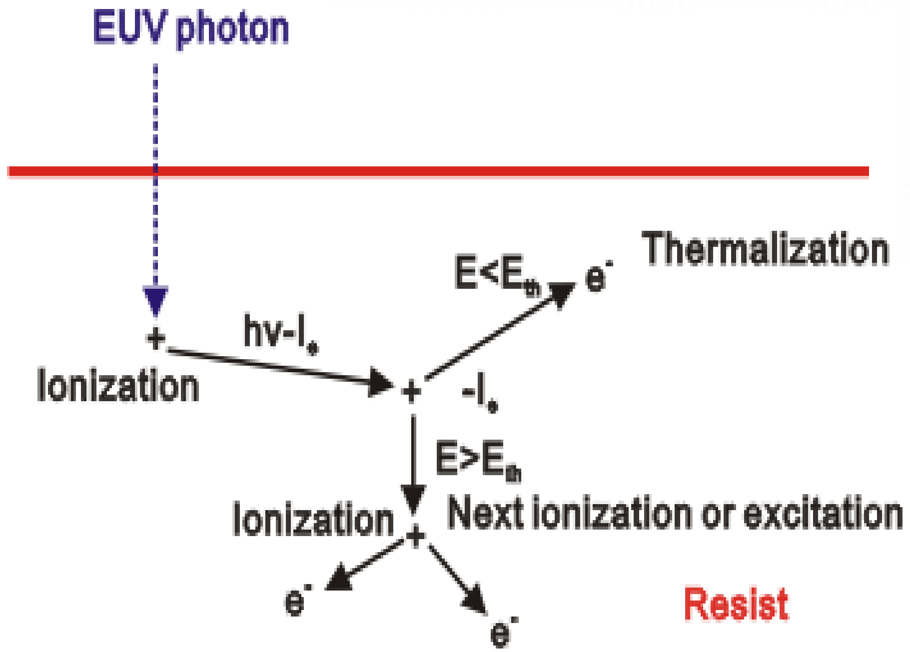
Chemically amplified resist



Resist sensitivity > 10mJ/cm^2 (10ns, 13.5nm)

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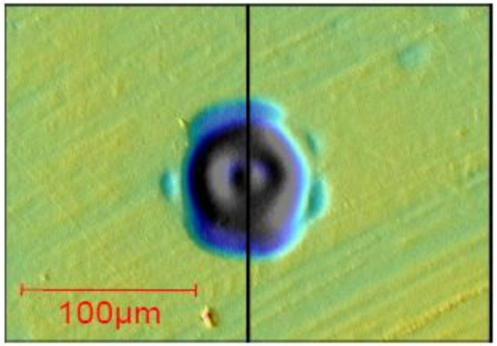
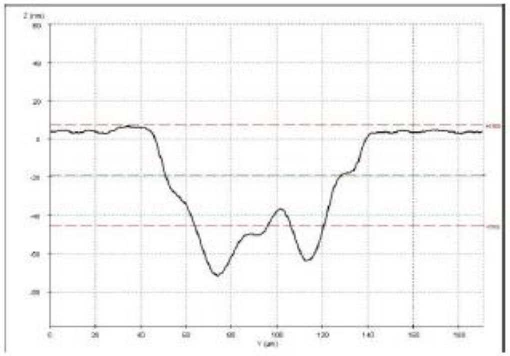
Ablation threshold

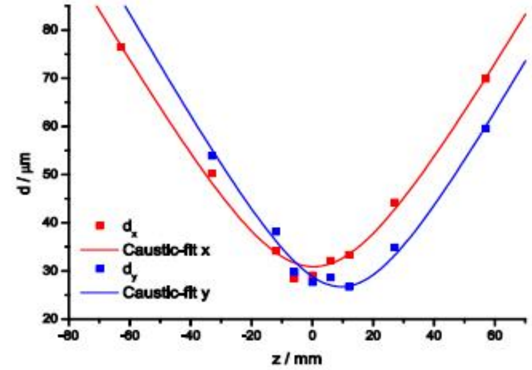
hilase

Second moment beam diameter from PMMA



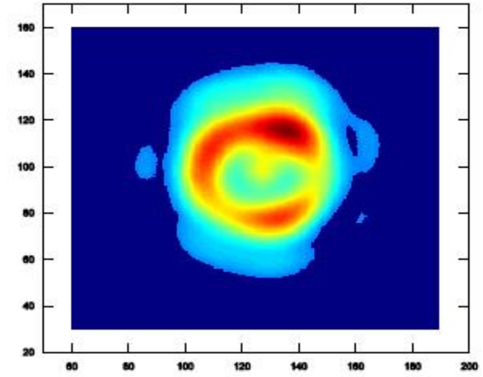


Ablative PMMA imprint, white-light interferometer



PMMA caustic

- Bulk PMMA sample at same position as phosphor
- Single pulses
- Assuming Lambert-Beer's law with
  - Ablation threshold 7.2mJ/cm2
  - Attenuation length 55.2nm
- Second moment beam diameter



Beam profile

Issue 1 : ablation threshold < resist sensitivity

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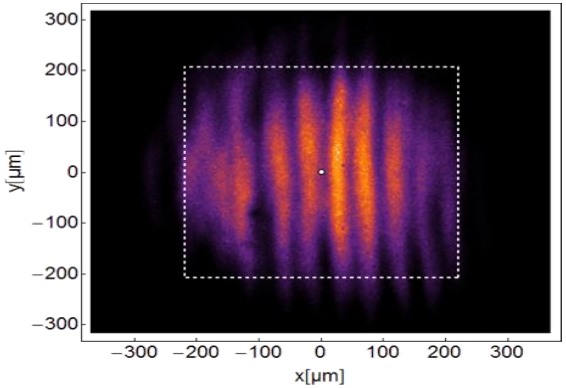
Spatial coherence

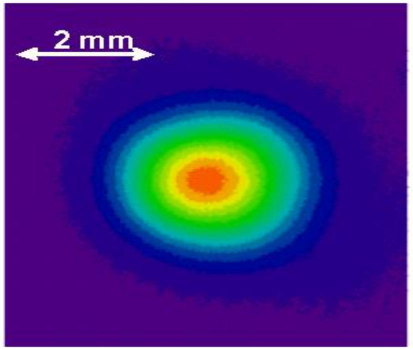
K of SASE FEL

~ 0.5



K of plasma source

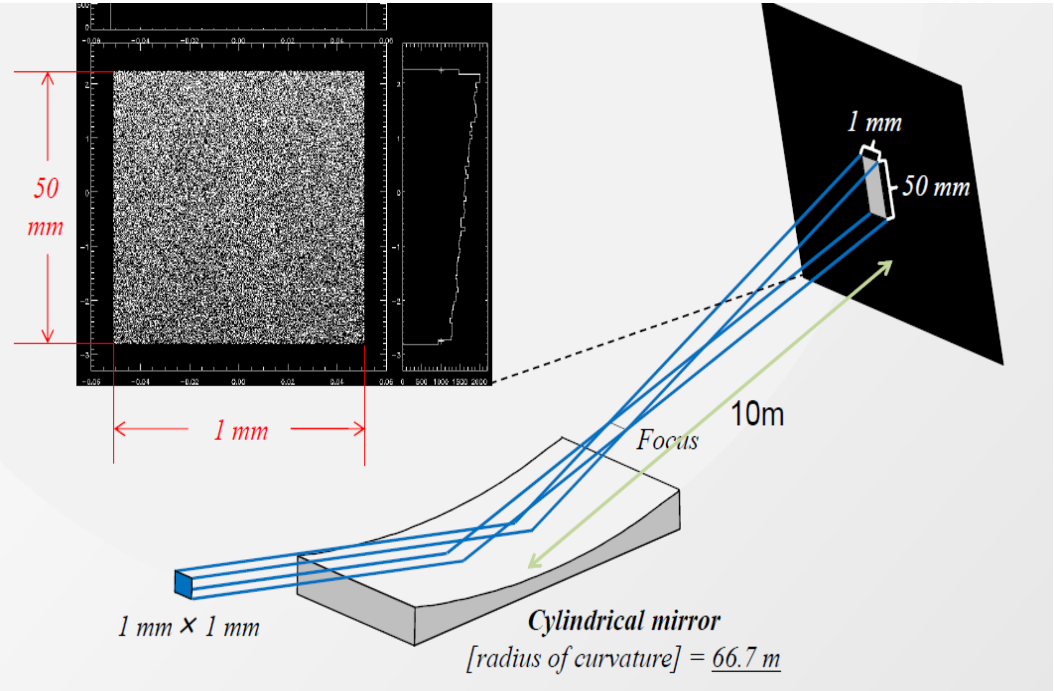
~ 3.2 x 10^{-9}

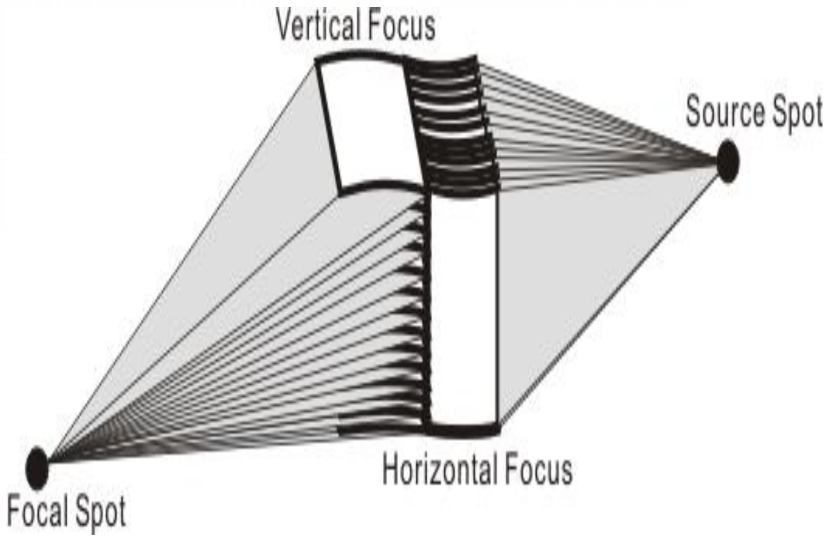


Issue 2 : interference pattern

Beam homogenizer by reflective optics

Possible beam expander and homogenizer for 13.5 nm applications (S81) L.Pina

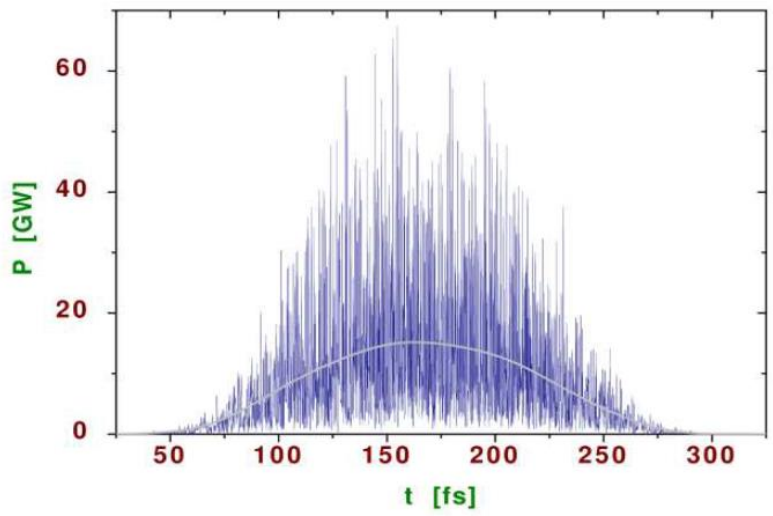




- **Low roughness surface to avoid speckle pattern generation**
- **Higher transmission for low loss**

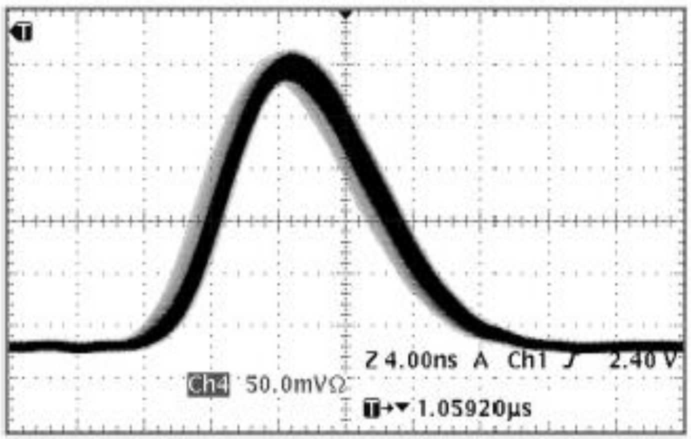
Temporal pulse structure

SASE FEL (FLASH)



E.A. Schneidmiller and M.V. Yurkov, Coherence properties of the radiation FLASH, FLASH Seminar, September 17, 2013

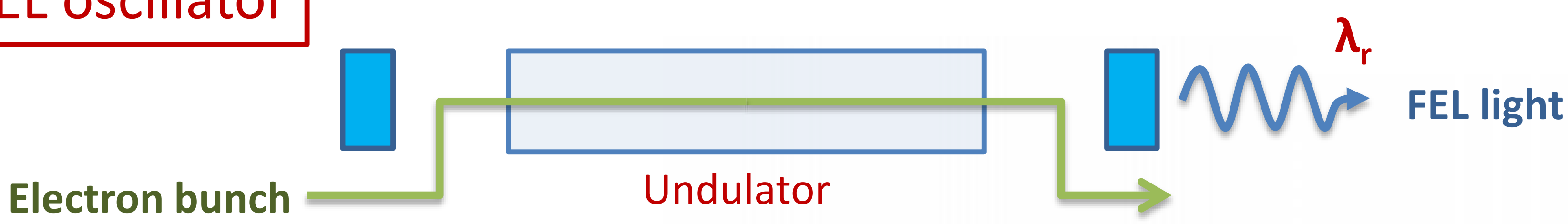
Sn laser plasma



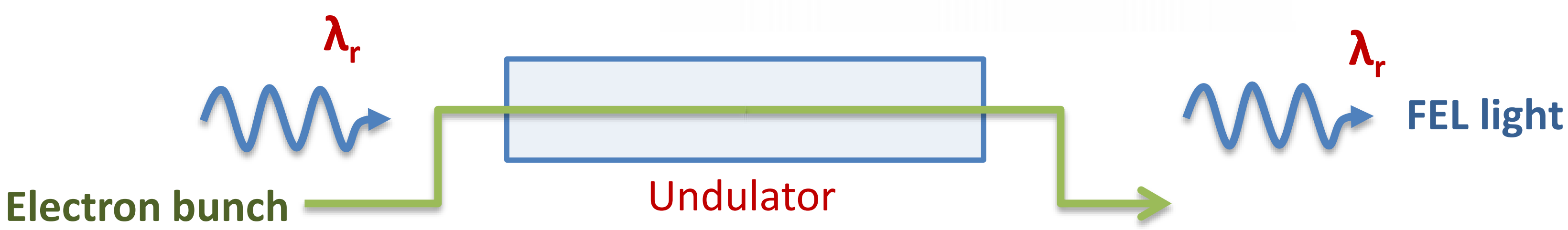
4ns/div

Temporal pulse control : seeding

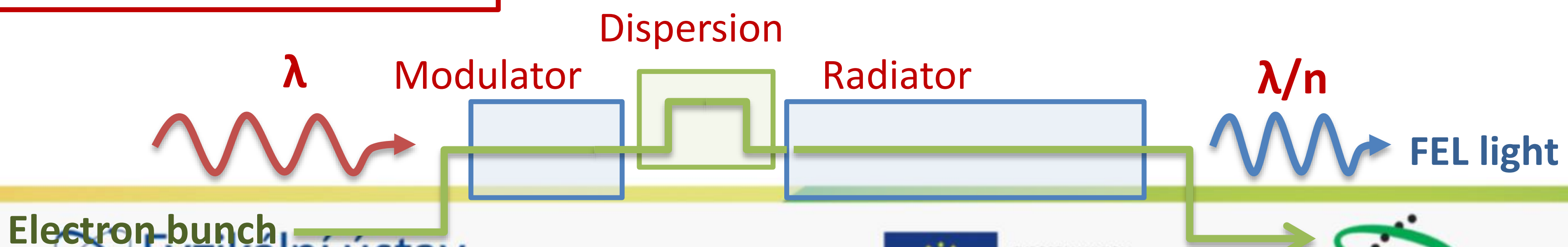
FEL oscillator



Single-pass FEL (Seeded)



Harmonic Generation



Seeded FEL in FERMI

ARTICLES NATURE PHOTONICS DOI: 10.1038/NPHOTON.2013.277

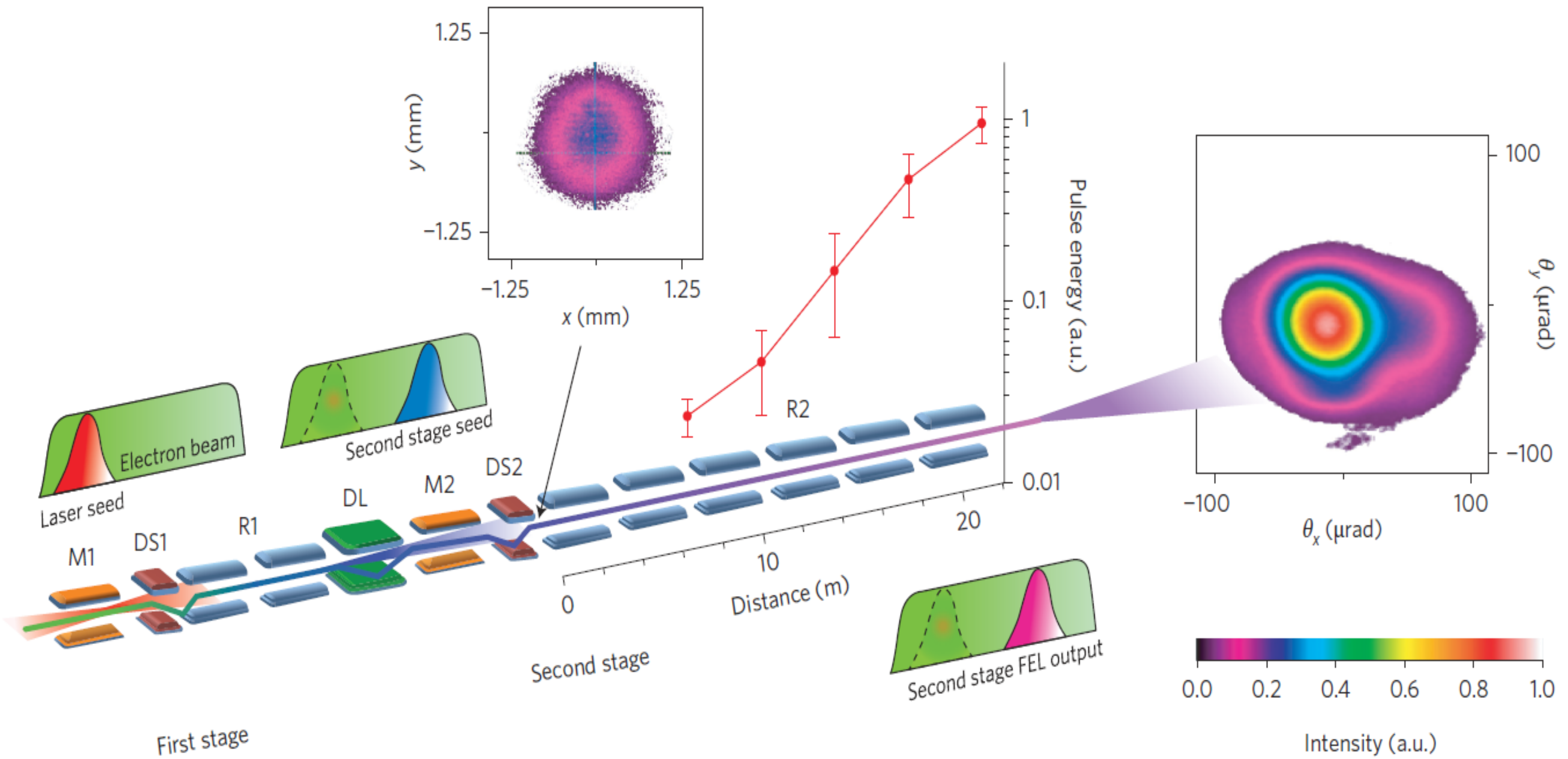


Figure 1 | Layout of FERMI's FEL-2 two-stage undulator line. The first stage, equivalent to the original Boscolo–Stagno converter[19], consists of an external seed modulating in energy the electron beam in the first-stage modulator (M1), followed by a dispersive section (DS1) that produces strong coherent bunching and subsequent coherent emission at a higher harmonic in the two first-stage radiators (R1). In the fresh bunch scheme[1], the first stage is followed by the delay line (DL), which ensures this radiation is superimposed temporally over a 'fresh' electron region in the second-stage modulator (M2) to begin the upshift process again. The second-stage radiators (R2) are resonantly tuned to a harmonic of the first-stage radiation. The exponential growth of the second-stage FEL output as a function of the number of resonant radiators is shown, together with the downstream transverse mode shapes of the radiation emitted by each stage (32 nm in the first stage and 10.8 nm in the second stage).

DOUBLE STAGE SEEDED FEL WITH FRESH BUNCH INJECTION TECHNIQUE AT FERMI*

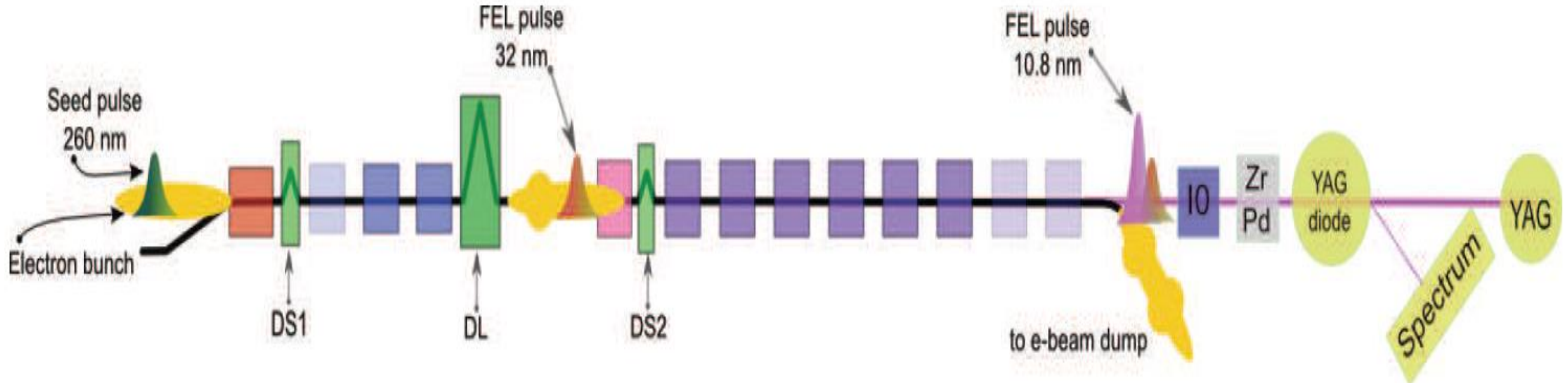
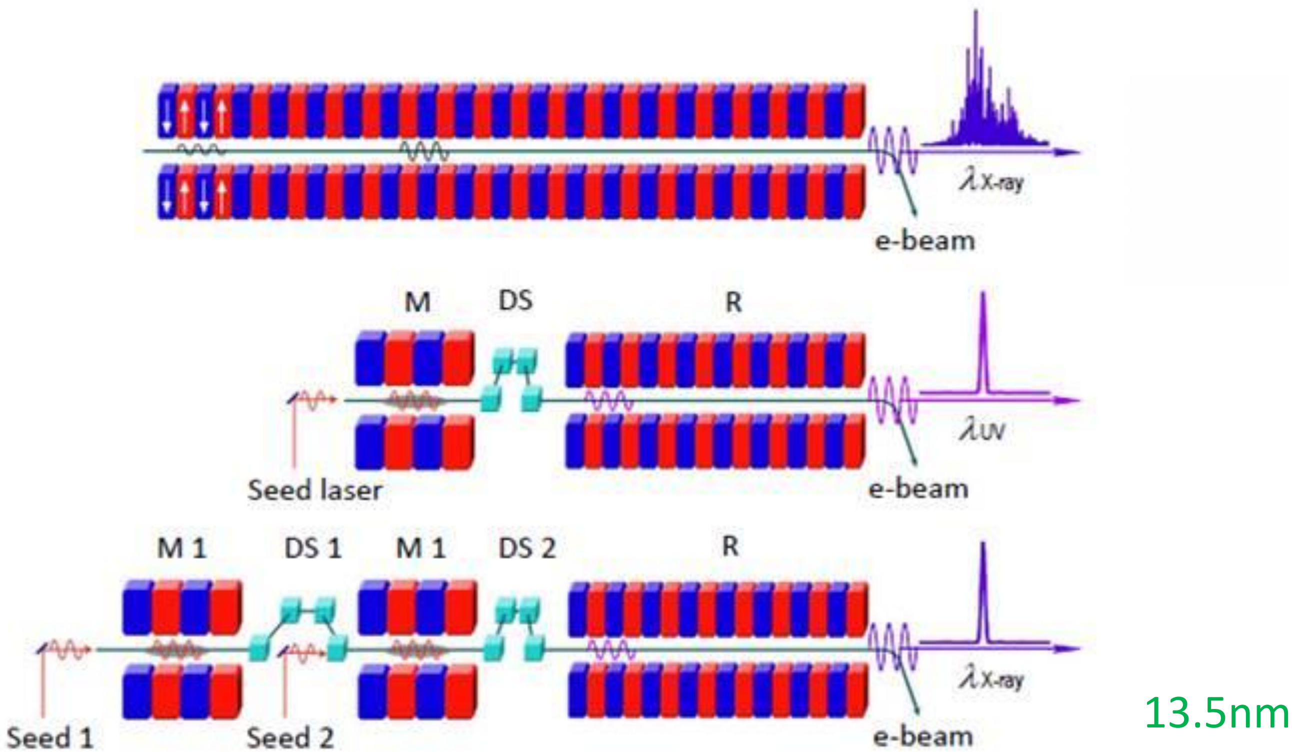


Figure 2: Layout of the undulator system of FERMI FEL-2 used for this work.

Seed pulse: 260nm, 180fs, 20μJ

10Hz,

Fresh bunch injection HGHG



13.5nm

324nm, 100fs, 20μJ

40.5nm

Fresh bunch injection HGHG

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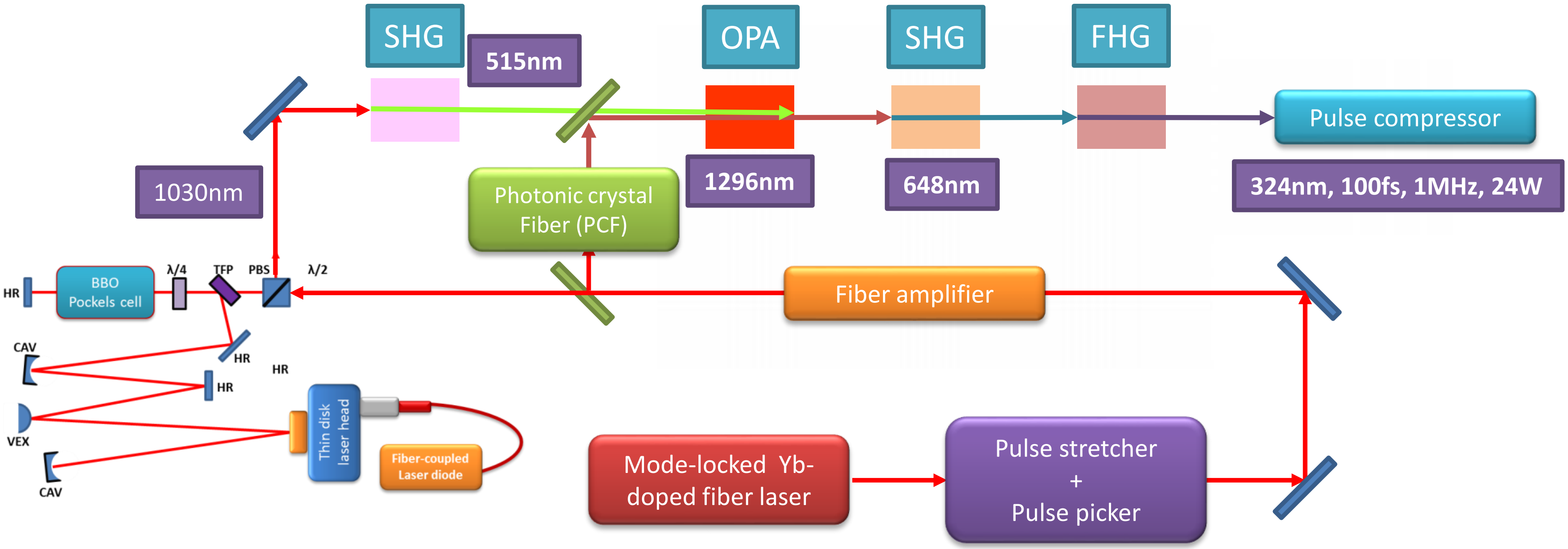
EUV FEL Seed Source



Development of High Repetition Rate Seed Pulse at 324nm for EUV-FEL using Picosecond Thin-disk Regenerative Amplifier (S53) Taisuke Miura

Perspective

- Scaling of EUV source over kW
- SASE FEL can generate over kW power at 13.5nm
- Matching of FEL pulse for lithography
    1. Resist sensitivity & ablation
    2. Spatial coherence reduction
    3. Temporal smoothing : MHz UV OPCPA seeder

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